A Three-Dimensional Eddy Census of a High-Resolution Global Ocean Simulation

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A 3D eddy census data set was obtained from a global ocean simulation with one-tenth degree resolution and a duration of seven years. Variables of interest include eddy diameter, thickness (vertical extent), minimum and maximum depth, location, rotational direction, lifetime, and translational speed. Distributions of these traits show a predominance of small, thin, short-lived, and slow eddies. Still, a significant number of eddies possess traits at the opposite extreme–thousands of eddies larger than 200 km in diameter appeared in daily data each year. We developed a new method of eddy identification that is well suited for global, 3D data sets and compares better with observations than previous methods.The eddy identification method has allowed us to locate and characterize 27 million eddies in the daily data and conduct detailed comparisons with surface observations.

How deep are ocean eddies? Do they look more like thin disks or tall columns? Do eddies with large surface extents tend to be deeper as well? How many eddies are completely hidden below the surface? These questions are difficult to answer with current observational data.

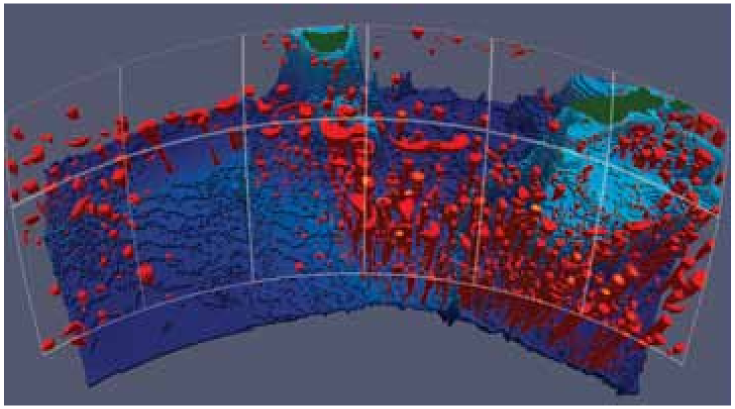

Fig. 1. Okubo-Weiss field in the Southern Ocean to the south of Tasmania and New Zealand, showing 120E-180E and 45S-55S. The Antarctic Circumpolar Current is the region with the largest number of eddies and the deepest eddies in the world. Many of these eddies extend to the full depth of the ocean, others are strictly surface features, and some are completely submerged. The R2 method is more discriminating and will eliminate many of the more spurious features seen here. Depth is exaggerated by a factor of 50.

Detailed eddy characteristics are available from satellite altimetry, but provide no information about depth. Shipboard observations provide some hints, but are limited to 2D sections and are often shallow in depth. Ocean floats are an important tool for collecting subsurface data and have begun to fill in gaps in recent years, but they provide only a few profiles for each eddy.

Numerical simulations of the ocean provide full 3D velocity and tracer fields that lend themselves to automated eddy census and tracking algorithms. The purpose of this work is to characterize eddies of the global ocean–in particular, properties involving depth that are somewhat sparse in observational studies. To our knowledge, this is the first such eddy census of a global ocean simulation. Past work on vertical eddy structure is limited to regional domains on continental shelves.

The characterization of ocean eddies is the first step towards understanding their effects in the transport of heat, salt, chemical species, and organisms. Observational studies have shown that discrete eddies can have a large impact on biological productivity–picophytoplankton biomass in individual eddies can be 30% higher than that of the surrounding waters.

The eddy census was conducted using velocity data from seven years of a high-resolution (one-tenth degree) simulation of POP (Parallel Ocean Program), developed and maintained by the Climate, Ocean, and Sea Ice team (COSIM) at LANL [1,2]. Current methods of eddy identification often use the Okubo-Weiss parameter, a measure of strain versus vorticity (Fig. 1). This method is unsuitable for global simulations because it detects many extraneous features and requires an arbitrary threshold that varies across the globe. A new method of eddy identification was developed, named R^2, that judges the fitness of a vortex based on similarity of characteristics with an idealized Gaussian vortex [3-5]. Eddies identified by the R^2 method are more realistic than those chosen by Okubo-Weiss when compared to observational data due to the retention of fewer spurious features.

Using the R^2 method, an eddy census database consisting of 27 million eddies was created from seven years of daily data [6]. This is an unprecedented amount of data on eddies in the global ocean. Statistics of eddy characteristics were analyzed and compared to observations, when available, and a tracking algorithm was created to find eddy lifetimes, and limit the study to long-lived eddies of at least four weeks [6].

Eddy diameter is a strong function of latitude, with smaller eddies near the poles and larger ones near the equator (Fig. 2). This is expected since the first baroclinic Rossby radius varies strongly with latitude and is also consistent with satellite observations. The Antarctic Circumpolar Current contains the thickest and highest density of eddies (Fig. 2).

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Funding Acknowledgments
DOE, Office of Science, BER, Regional and Global Climate Modeling programs and Climate and Earth System Modeling programs; LANL National Security Education Center

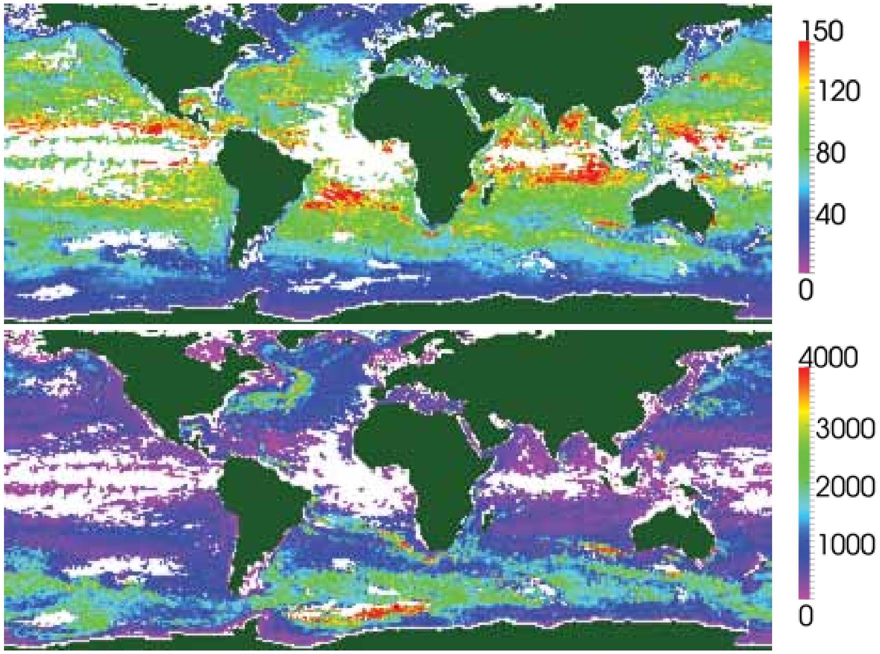

Fig. 2. Eddy statistics from seven years of a POP ocean simulation using the R^2 eddy detection method, a minimum lifetime of four weeks, and collated in one-degree bins: diameter, km (top); thickness, m (bottom). The Antarctic Circumpolar Current stands out as the region with the most eddies and the deepest eddies. Deep eddies also appear in the Gulf Stream, Kuroshio Current, and Agulhas Ring pathway. White areas are one-degree cells where no eddies were detected over the seven-year census.

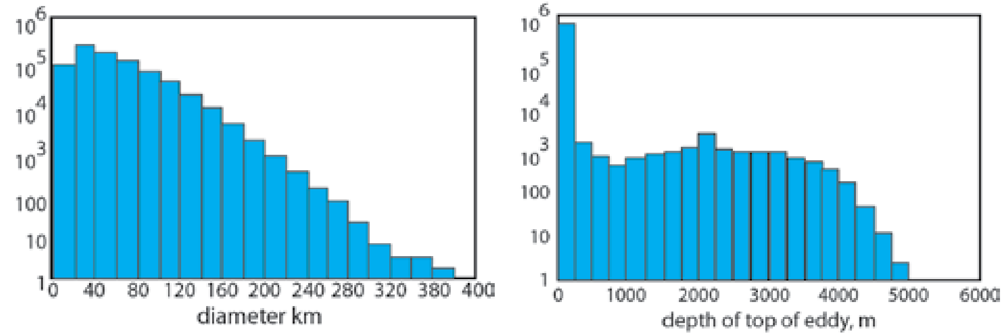

Fig.3. Distribution of eddies detected by diameter (left) and depth of the top of the eddy (right), using the R^2 method and minimum lifetime of four weeks. This is the population of eddies recorded in daily averages, and vertical axes display number of eddies per year. The majority of eddies are small and thin, but there are still thousands of eddies with diameters greater than 200 km, and tens of thousands with thicknesses of 4000–5000 meters. The great majority extend to the surface, but tens of thousands exist below the surface.

Thick eddies are also common in the Gulf Stream, Kuroshio Current, and Agulhas ring pathway.

A significant number of eddies penetrate deep into the ocean: a third of the eddies in this simulation are at least 1000 meters tall. Of eddies with a minimum four-week lifetime, the majority (97%) extend all of the way to the surface (Fig. 3). Although not all of these surface-expressed eddies located by the R^2 method are clearly reflected in the surface height, it is very likely that satellite altimetry-based assessments of eddy size, spatial distribution, and lifetime are reasonably comprehensive as estimates of eddy characteristics. The remaining eddies that do not reach the surface are distributed over the full depth of the ocean, with thousands deeper than 3000 meters. Larger-diameter eddies are likely to be thicker, longer-lived, and faster than smaller-diameter eddies. Correlations between thickness and lifetime or thickness and speed are weak, except that very thin eddies are fast and shorter-lived.

We can confidently conclude that eddies are a common phenomenon in the deep ocean, albeit in smaller numbers than thin eddies near the surface. Observational studies of eddy transport of heat and nutrients have been confined to the upper ocean for practical reasons. The next step in the analysis of this simulation is to quantify the impact of discrete eddies on the transport of tracers throughout the globe. Indeed, high-resolution ocean model output provides a unique opportunity to compute detailed statistics where observations are sparse.

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